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An Optical Profilometer for Spatial Characterization of Three-Dimensional Surfaces

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SUMMARY

A technique is described for obtaining spatial characterization of three-dimensional surfaces with uniform near-Lambertian reflectance using a noncontact optical profilometer. The design concept and system operation are discussed, and a preliminary evaluation of a breadboard system is presented to demonstrate the feasibility of the optical profilometer technique. Measurement results are presented for several test surfaces; and to illustrate a typical application, results are shown for a cleft palate cast used by dental surgeons. Finally, recommendations are made for future development of the optical profilometer technique for specific engineering or scientific applications.

INTRODUCTION

In manufacturing, engineering, and medical research, spatial characterization of a three-dimensional surface is often required. An electromechanical probe which rides on the surface of the sample is usually used. Occasionally, a noncontact method is required to prevent damage to the surface to be measured.

Optical techniques can be used to provide noncontact surface characterization. Drawing contour lines from a pair of stereo pictures with the aid of a drawing machine is most commonly used, but this method is not direct and requires expensive instruments. Another optical technique, called moiré topography (ref. 1), produces a contour line system on the sample surface. These optical techniques require additional processing to convert the contour lines to surface depths in digital form when the surface characterization is to be stored or manipulated in a computer.

The purpose of this paper is to describe a relatively simple and inexpensive electrooptical technique which provides digital information for the spatial characterization of three-dimensional surfaces. The optical profilometer concept consists of an optical system and photodetectors which observe the change in the energy distribution of an image spot of light as a function of the depth of the sample surface at the measurement point. The sample surface is scanned to provide measurement information over the complete surface. Changes in the output signal due to variations in surface slope, surface reflectance, and lamp intensity are greatly reduced by taking the ratio of the sample photodetector output to a reference photodetector output. Since the profilometer observes the reflected light from the test surface, its use is limited to sample surfaces which have a uniform near-Lambertian reflectance or which can be temporarily coated.

A breadboard optical profilometer has been developed and tested to demonstrate the feasibility of the optical profilometer concept. Measurement results are presented for several test surfaces to illustrate the operation and performance. To illustrate a typical application, measurement results are presented for a cleft palate cast used by dental surgeons to aid in the surgical reconstruction

of the palate. In addition, recommendations are made for further development of the instrument concept to meet specific engineering or scientific requirements.

SYMBOLS

d	depth, mm
V_D	output of voltage divider, V
V_r	output of reference detector, V
V_s	output of sample detector, V
X	axis along scan line
Y	axis perpendicular to scan lines
Z	vertical axis (depth)
θ	angle between surface normal and optical axis, deg
ρ	surface reflectivity

Abbreviation:

A-D	analog to digital

DESCRIPTION OF CONCEPT

As shown in figure 1, the basic configuration of the optical profilometer consists of an electrooptical system, a microprocessor, and a data recorder.

Electrooptical System

The electrooptical system provides an output voltage which is a function of the sample depth at the point of measurement. A light source is imaged by the lens into a spot on the sample surface. As the surface depth increases, the imaged spot becomes defocused and the spot size increases. The spot is reimaged by the lens and directed by a beam splitter to two photodetectors to provide sample and reference signals.

The sample detector, which acts as a field stop, is sufficiently small to view only the center portion of the spot and hence to observe a decrease in energy as the spot becomes defocused because of changes in sample depth. The energy reflected by the sample surface and observed by the sample detector is also dependent upon the illumination scattering function, which describes the angular dependence upon viewing and illumination geometry.

Since the output voltage of the sample detector depends not only on the surface depth but also on the surface slope, a reference detector is used to observe the entire spot. A field lens is positioned to image the imaging lens onto the reference detector. The reference detector, therefore, collects all of the energy of the defocused spot which is reflected into the solid angle subtended by the imaging lens. This configuration almost entirely removes the reference detector's dependence on surface depth but does not affect its dependence on the average surface slope and reflectivity. By dividing the sample detector output by the reference detector output, the dependence on slope and surface reflectivity can be removed, since both detectors have the same viewing axis. The voltage divider output can be described as

$$V_D(d) = \frac{V_S(d,\theta,\rho)}{V_r(\theta,\rho)} \qquad (1)$$

where V_S is the sample voltage, V_r the reference voltage, θ the angle between the surface normal and the optical axis, d the depth, and ρ the surface reflectivity. The output of the voltage divider is then amplified, digitized, and read by the microprocessor.

Microprocessor

The microprocessor serves as the control unit, provides data storage, performs minimal data processing, and formats the output for the data recorder. A simple 4-bit microprocessor with 4000 4-bit word storage was used to provide an economical, yet flexible, control unit. Commands to the microprocessor are entered through a standard teletype, although several push-button switches would be sufficient. The microprocessor sends control signals to two stepper motors which drive gear assemblies to move the sample platform along the X- and Y-axis during data acquisition.

The microprocessor is used to command the analog-to-digital conversion (8 bits) and to read and store the digital data for each scan line along the X-axis. Data obtained from a scan line are compared with the data obtained during calibration to determine the appropriate output for representing surface depth at each measurement point. After each X-axis scan, digital data are output to the data recorder.

The microprocessor can also be used to automatically scan a calibration surface and store the data for comparison with subsequent sample data. This means of simple data processing is used since the variation of voltage with depth is not linear.

Data Recorder

The electrooptical system and the microprocessor provide data pertaining to the sample surface in several forms available for recording. Output data can be recorded in analog form by recording the motor step commands (for X and Y position) and the output voltage of the voltage divider (Z information). Digital data can be recorded from the microprocessor as 8-bit raw data or, after

comparison with calibration data, as depth information. The breadboard system described in this paper compares the raw data with calibration data and assigns an alphabetical character to be typed on the teletype. More sophisticated output display features, such as three-dimensional contour plots, surface areas, and surface slopes, could be obtained with additional storage and computational capability in the computer control unit.

DEVELOPMENTAL SYSTEM

A breadboard system was fabricated to evaluate the optical profilometer concept as a technique for generating three-dimensional data for surface characterization. The breadboard system is shown in figure 2, and pertinent design parameters are listed in table I.

Operation

Calibration of the optical profilometer is initiated by a command from the teletype to the microprocessor. The sample platform is then automatically moved to position the calibration surface in the optical path. The calibration surface consists of a wedge which provides a linear change in depth along the X-axis. As data are taken, the sample platform is automatically moved in equal increments along the X-axis. These digital data, which are a function of surface depth, are stored in tabular form by the microprocessor. With this calibration procedure, the slope of the calibration wedge determines the profilometer depth range and resolution within the operating limits.

Upon completion of calibration, the sample platform is automatically returned to the initial position. Manually, the operator vertically positions the sample platform so that the highest point on the sample is slightly below the maximum calibration height. Data acquisition is initiated by a teletype command, and the platform is moved in equal increments along the X-axis after each data point is taken and stored by the microprocessor. At the completion of each scan line the sample data are compared with the calibration data to select an output character to represent vertical height for each measurement point. Output data are displayed for the entire scan line, and the platform is returned along the X-axis and incremented along the Y-axis for the next line. The platform is returned to the initial position at the completion of all data acquisition.

The format selected for output data on the teletype consists of the 26 characters of the alphabet with A representing the highest depth interval and Z the lowest. The symbol @ is used to indicate surface depths above the highest calibration point and the period (.) is used to indicate depths below the lowest calibration point. The surface depth interval represented by a character is determined by the slope of the surface used for calibration. Only 26 calibration points are needed to display the output data in this form. Additional display options include printing only a single line of output characters or printing both the calibration and the sample data in hexadecimal format.

Evaluation

Data were obtained from several test surfaces to demonstrate the operation and evaluate the performance of the breadboard optical profilometer. Figure 3 shows a plot of digitized voltage divider output for a calibration wedge providing a depth range of approximately 14 mm. The output voltage is a nonlinear function of depth, with diminishing depth resolution as the surface depth increases. This nonlinear function is essentially linearized by the microprocessor by storing calibration data for equal depth intervals in a look-up table.

To define an approximate depth resolution limit for the breadboard electro-optical system, the wideband root-mean-square noise voltage was measured at the output of the voltage divider and found to be 1.9 mV. As evident from the voltage-depth curve shown in figure 3, the poorest depth resolution occurs near the maximum depth, where the slope can be approximated as 0.155 V/mm. For a minimum analog signal-to-noise ratio of 4, the minimum detectable depth interval would be on the order of 0.05 mm. Higher analog signal-to-noise ratios would occur for smaller surface depths, and better depth resolution could be obtained by reducing the total depth range. These results are, of course, dependent upon the particular lens and apertures used in the breadboard system and could be modified by designing the optical system for a specific application.

To test the performance of the breadboard system, the calibration wedges described in table II were used as sample surfaces. Wedge C, which provides depth resolution of 0.53 mm over a 14-mm range, was used for calibration, and data were obtained for wedges A and B as sample surfaces. The sample platform was lowered 1.9 mm for wedge A and 3.8 mm for wedge B to place the sample surfaces in the approximate center of the depth range. Output data, plotted in figures 4 and 5, accurately characterize the sample surfaces. For actual operation using sample surfaces with small depth variations, more precise results could be obtained by using the appropriate calibration wedges. On both wedges, the same line along the X-axis was scanned several times with identical output characters produced on the teletype, indicating excellent measurement repeatability.

Data were obtained from a section of a sphere with a known radius (33.1 mm) to verify that the profilometer output was not adversely affected by variations in surface slope. Initial results, which did not reconstruct the sphere radius to the accuracy expected, indicated that the slope dependence was not effectively being removed. Further investigation revealed that both photodetector outputs contained offset voltages. While the sample detector offset was considered negligible, the reference detector offset was significant. The reference detector offset voltage resulted from radiation reflected from the surfaces of the several elements in the imaging lens. Since this offset voltage was not a function of surface slope, proper operation of the division function (eq. (1)) was not possible.

To provide a temporary solution, the reference detector offset voltage, due to the surface reflections of the lens, was measured. A constant voltage equal to the offset was subtracted from the reference signal by an operational amplifier in a subtraction mode.

After completing this modification, the profilometer was recalibrated and measurements were repeated for the spherical surface. Output data for the entire surface are shown in figure 6. In figure 7, the center line of output data is plotted to compare with a circular arc of the same radius as the sphere. Data are plotted as blocks with dimensions equal to the sample interval along the X- and Z-axes to allow direct comparison between the output results and the actual surface characteristics. The larger depth values approach the worst-case measurement conditions for depth range, slope change, depth resolution, and small signal output for the breadboard design. The close agreement between output data and the actual surface illustrates the feasibility of the optical profilometer technique for characterizing three-dimensional surfaces.

To illustrate a typical application (ref. 2), data were obtained for a cleft palate cast, which is used by dental researchers in the surgical repair of craniofacial disorders. Calibration was performed with wedge C, and results are shown in figure 8 along with a photograph of the cleft palate cast in figure 9.

It should be noted that the performance of the breadboard developmental system was limited by the 26-character format of the output data; therefore, the results illustrated here do not represent the limiting performance of the electro-optical design.

POTENTIAL IMPROVEMENTS

A breadboard system was developed to determine the feasibility of the optical profilometer concept. During the development, several design areas were recognized in which performance could be improved or the system adapted to meet specific requirements.

Optical System

The depth range could be increased or decreased for a particular application by selecting the lens focal length and lens diameter. To tailor the optical design to achieve a specific depth range, trade-offs should be made regarding the size and types of apertures for the light source and both detectors. Considerable flexibility exists in defining the size and intensity distribution of the defocused spot, which affect the linearity of the output voltage as a function of depth and the spatial resolution on the sample surface.

A permanent and more accurate solution to the problem of voltage offsets due to front surface reflections from the lens is provided by an alternate optical design. The light source should be moved to the sample side of the imaging lens to prevent the front surface reflections from reaching the detectors. This can be accomplished by using a second lens to image the light source on the sample and by using a beam splitter in place of the folding mirror, as shown in figure 10.

Microprocessor and Electronic System

The signal-to-noise performance may allow additional encoding levels to be used to improve system resolution and precision. System performance may improve by performing the division digitally with the microprocessor to avoid errors due to analog offsets in the analog voltage divider. Since the step interval along both the X- and the Y-axis is under microprocessor control, decreasing the step interval between data samples, which increases sampling frequency, can be investigated to improve the precision in measuring surface characteristics. Additional microprocessor capability would allow surface areas and slopes to be calculated, and for industrial engineering applications, the microprocessor could format the digital output data to interface readily with digitally controlled machinery.

Output Data Display

The teletype used with the breadboard system represents the simplest form of output device which could be readily interfaced to a microprocessor. A simple microprocessor could also use a line printer, magnetic tape, paper tape, cathode-ray tube (CRT) display, or a digitally controlled plotter as an output display device. All of these options would display data with higher resolution in a manner particularly suited to the user.

CONCLUDING REMARKS

An optical profilometer concept for obtaining spatial information for characterization of three-dimensional surfaces has been investigated. The basic concept utilizes the change in the energy distribution of an imaged spot of light as the image moves out of focus to provide a photodetector output voltage which is a function of surface depth. Variations in the output signal due to changes in surface slope or reflectivity and light source intensity are greatly reduced by taking the ratio of the sample photodetector output to a reference photodetector output. Operation of a breadboard profilometer, which uses a microprocessor to control sample position, calibration, and simple data processing, was described.

A preliminary evaluation of the profilometer was performed by obtaining data for several test surfaces. Depth resolution of 0.53 mm over a 14-mm range was obtained with the breadboard developmental system which was limited by the 26 output characters. Measurements of noise voltage indicate that depth resolutions approaching 0.05 mm over a 14-mm depth range for a desired signal-to-noise ratio of 4 appear feasible with the breadboard optical system. Improved depth resolution could be achieved by operating over a smaller depth range. Data which accurately characterized a spherical surface were obtained to illustrate that variations in surface slope do not significantly affect system performance. Future developmental work on the optical profilometer should consider (1) tradeoffs within the optical design to optimize the depth resolution and range, (2) separation of the optical path of the light source from that of the detector,

and (3) expansion of the microprocessor capability to improve the processing and display of data.

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REFERENCES

1. Takasaki, H.: Moiré Topography. Appl. Opt., vol. 9, no. 6, June 1970, pp. 1467-1472.

2. Berkowitz, Samuel: Stereophotogrammetric Analysis of Casts of Normal and Abnormal Palates. Amer. J. Orthod., vol. 60, no. 1, July 1971, pp. 1-18.

TABLE I.- DESIGN PARAMETERS FOR BREADBOARD OPTICAL PROFILOMETER

[One-to-one imaging system used]

Focal length of imaging lens, cm	16.5
Diameter of imaging lens, cm	6.4
Aperture diameter of reference photodetector, cm	0.31
Aperture diameter of sample photodetector, cm	0.05
Reference photodetector	UDT PIN-5
Sample photodetector	HP 5082-4205
Microprocessor	Intellec 4
Sample interval along X-axis, cm	0.079
Sample interval along Y-axis, cm	0.13
Sample interval along Z-axis (wedge C), cm	0.053
Range along X-axis, cm	5.5
Range along Y-axis, cm	5.5
Range along Z-axis, cm	1.4

TABLE II.- CALIBRATION WEDGES

Wedge	Depth range, cm	Depth interval per output character, cm	Slope
A	0.45	0.018	0.091
B	.91	.036	.18
C	1.4	.053	.27

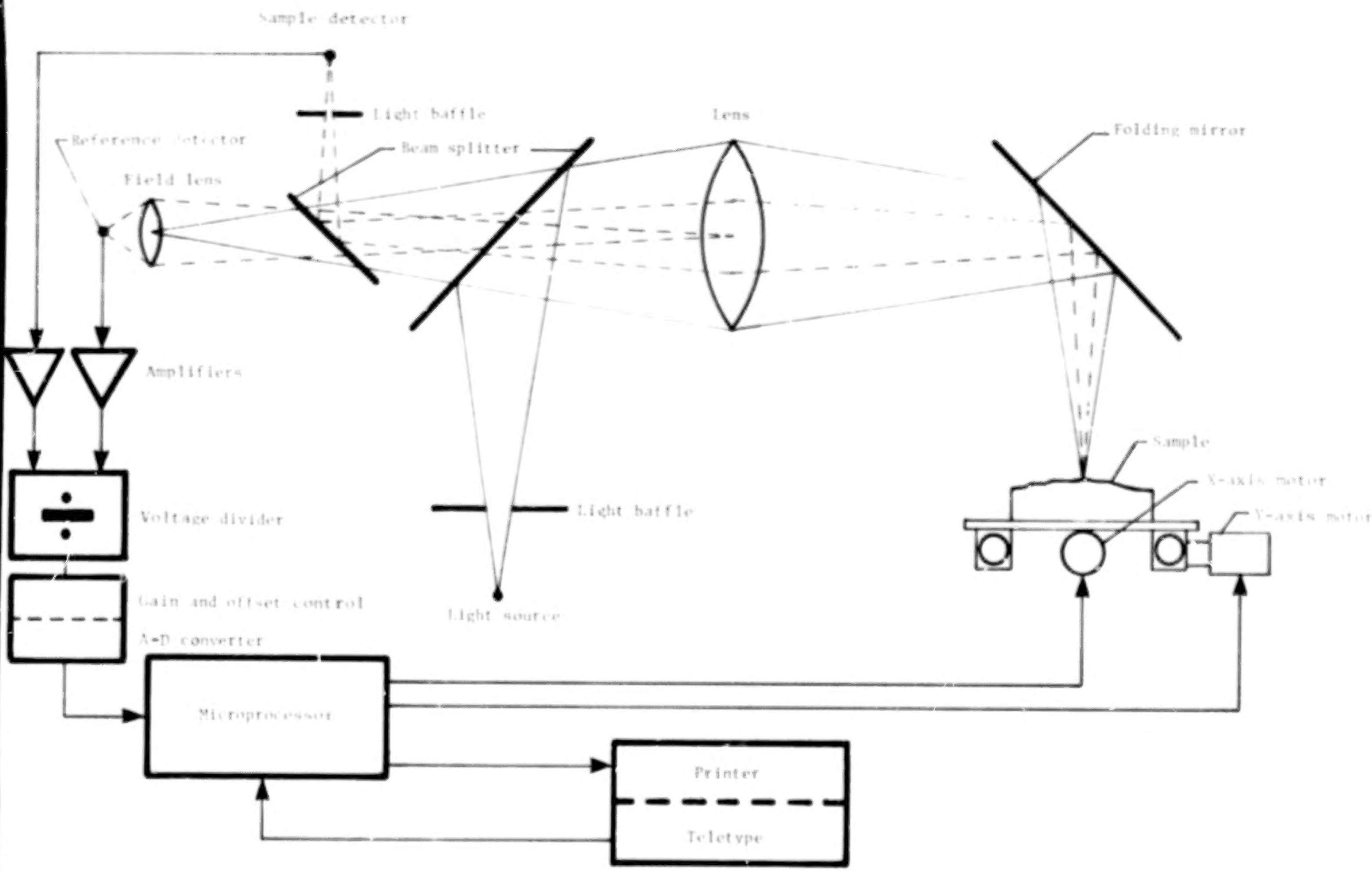

Figure 1.- Basic configuration of optical profilometer.

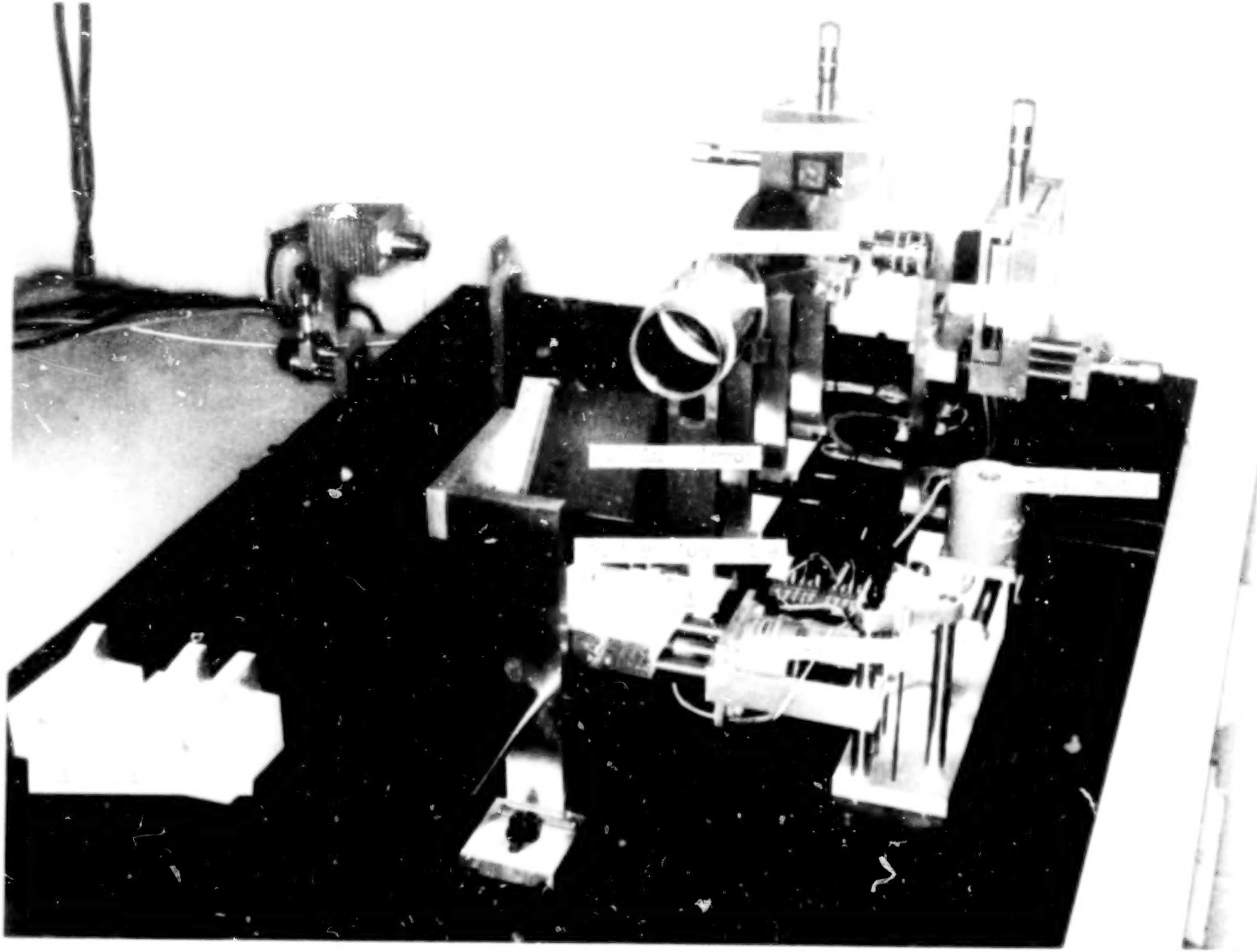

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Figure 2.- Breadboard optical profilometer.

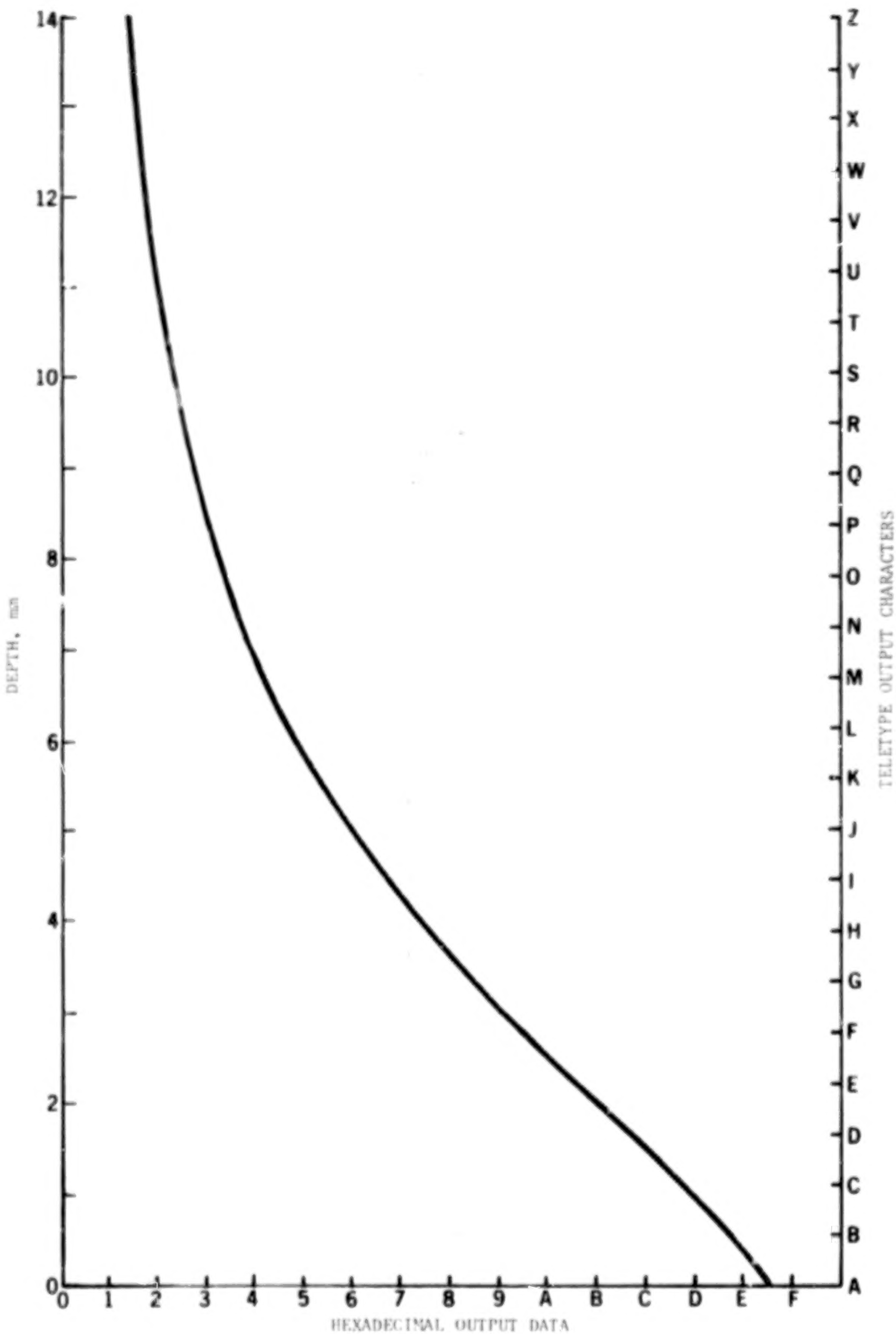

Figure 3.- Profilometer output data (digitized output voltage) as a function of depth.

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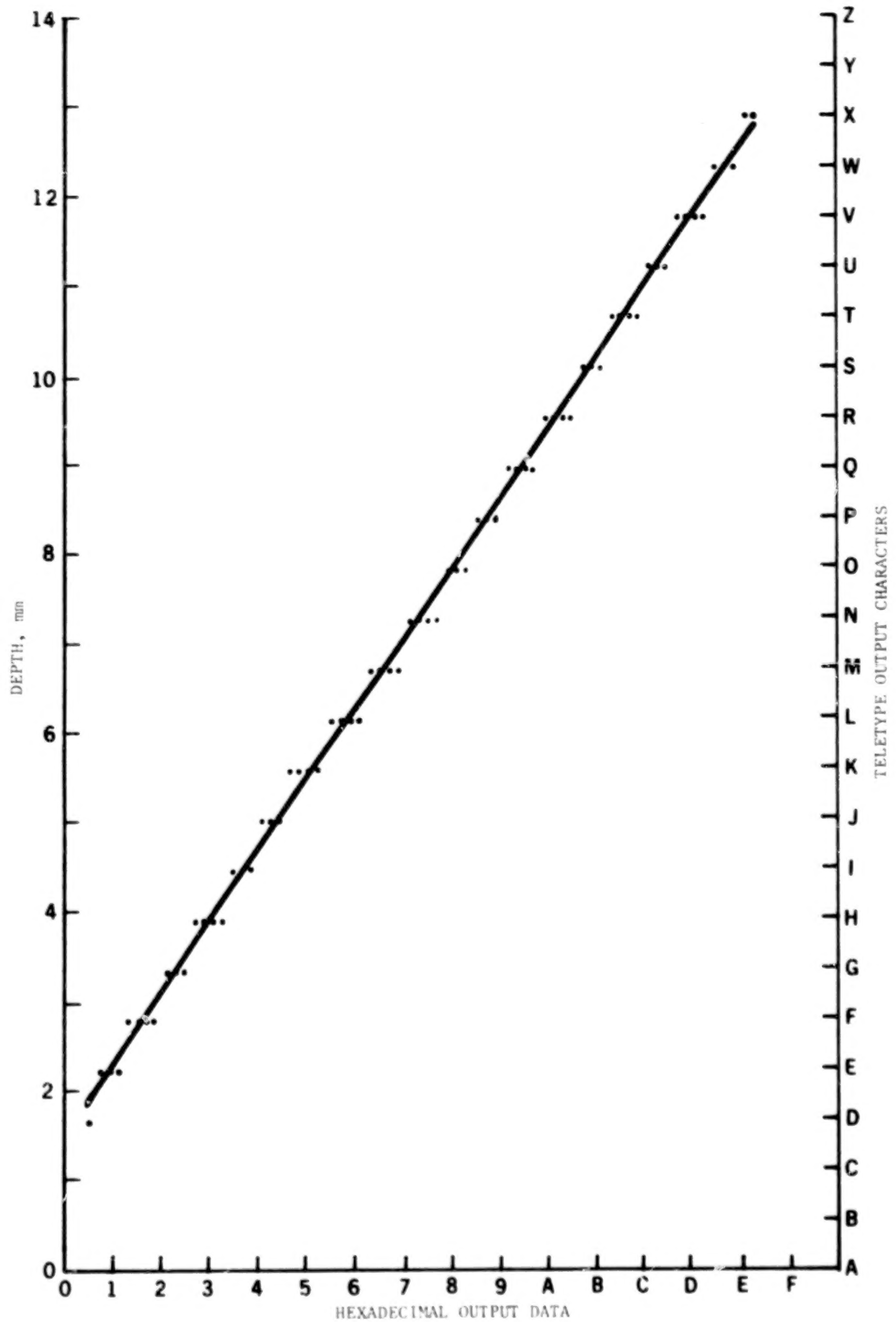

Figure 4.- Profilometer output data (digitized output voltage) for wedge A with wedge C used for calibration.

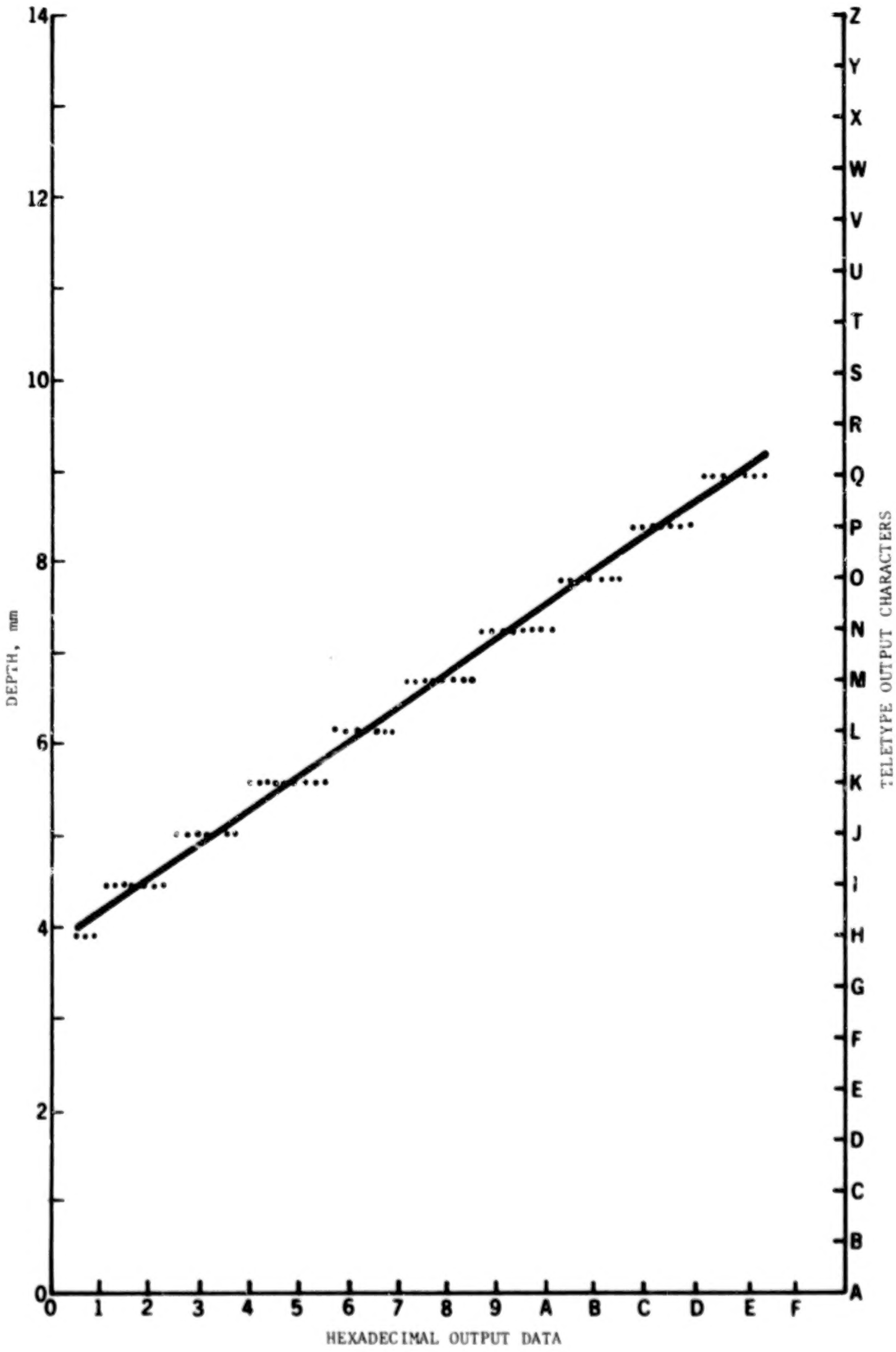

Figure 5.- Profilometer output data (digitized output voltage) for wedge B with wedge C used for calibration.

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R
.................................ZZZZZZ................................
........................ZYYXXXXWWWWWWXXXYYYZ...........................
....................YYXXWVVVUUUUTTTTTTUUUUUVVWWXYYZ....................
.................YYXWVVUTTTSSSRRRRRRRRRRSSTTTUUVWXXY...................
..............ZYXWVUUTSSRRQQQPPPPPPPPPPPPQQQRRSSTTUVWXYZ...............
............ZYXVUUTSRRQQPPPOOONNNNNNNNNNNOOOPPPQRRSTTUVWYY.............
..........ZYXVUTTSRQQPPOONNMMMMMLLLLLLMMMMMNNOOPPQRRSTUVWYZ............
.........YXWUUTSRQPPONNMMMLLLKKKKKKKKKKKKLLLMMMNOOPQRRSTUWXY...........
.......ZYWVUTSRQPPONMMMLKKKJJJJIIIIIIIIIJJJKKLLMMNNOPQRRTUVWYZ.........
......ZXWVUTRQQPONMMLLKKJJIIIIHHHHHHHHHHHHIIIIJJKKLLMNNOPQRSTUWXZ......
.....ZXWUTSRQPONNMLLKJJIIIHHHGGGGGGGGGGGGHHHIIJJKKLLMNOPQRSTUWXY.....
....ZXWUTSRQPONMMLKJJIIHHHGGGFFFFFFFFFFFFGGGHHHIJJKKLMNNPPRSTUWXZ....
....YWVTSRQPONMLKKJJIHHGGGFFFEEEEEEEEEEEEEEFFFGGHHHIJJKLMMNOPRSTUWXZ...
...YWVUSRQPONMLKKJIIHHGGFFEEEEDDDDDDDDDEEEEEEFFGGHHIIJKLMMNOPRSTUWY...
..ZXVUTRQPONMLKKJIIHGGFFEEEDDDDDCCCCCCDDDDDEEEFFGGHIIJKLMNNPQRSUVXY..
..YWUTSRQPNMLLKJIHHGGFFEEDDDCCCCCCCCCCCCCDDDEEEFFGGHIIJKLMNOPQRTUWY..
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.YXVTSRQONMLKKJIHHGFFEEDDCCCBBBBBBBBABBBBBCCCDDDEEFFGHHIJKLMNOPQSTVXY.
.YWUTSQPONMLKJIIHGGFEEDDDCCBBBBAAAAAAAAAABBBBCCDDEEFFGGHIJJKLMNPQRTUWY.
.YWUTRQPONMLKJIHHGFFEEDDCCCBBBAAAAAAAAAAAABBBCCCDDEEFFGHIIJKLMNPQRSUWX.
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.YWUTRQPONMLKJIHHGFFEEDDCCCBBBAAAAAAAAAAAABBBCCCDDEEFFGHIIJKLMNPQRTUWX.
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.YXVTSRQONMLKKJIHGGFFEEDDCCCBBBBBBBBABBBBBCCCCDDEEFFGHHIJKLMNOPQSTVWY.
.ZXVUTRQPONMLKJIIHGGFFEEDDDCCCBBBBBBBBBBBCCCCDDEEFFGGHIJJKLMNOQRSUVXZ.
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...................YYXWWVVUUUTTTTTTTTTTTUUUVVWWXYZ...................
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............................ZZZYYYYYYYYZZZ............................
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Figure 6.- Profilometer output data for spherical surface.

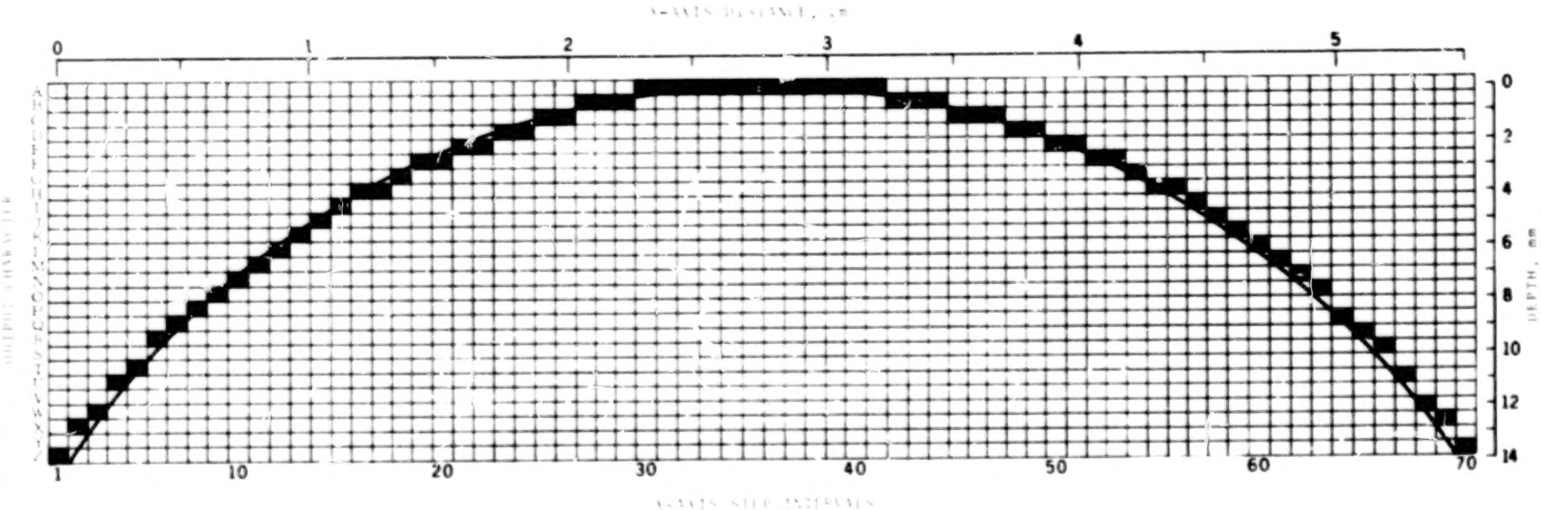

Figure 7.- Single scan line through center of spherical surface.

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R
.........................ZYXWVVUUVWWY..................................
..............................ZYYYYYZ..................................
................. ........YTSSSSSSRSRPQRRSTW........................
.......ZVXZ...........QMLKKJJJJKKKLLLLMNOQSUZ........................
.......USSTTTV........YOLKJJJIIIJJJJKLKLLMNOPQSW.........ZZZ..........
.......TSSSSSTV.......UOMKJIIJJJKKLKKMLMMMNOOPRT.......ZYYYYYZ........
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.......RRRRRSSTUW.......WSPNNNNOONMMMOQRRQQQRSV......ZYYYYYXXXZ.......
.......RRRRRRSTTUW.........VTSRQPOOOPTUUTTTUVX......ZYXWWXXWWX........
.......QQRRRRSSTTUVX..........WVTTSTWY.............ZXWWVVWWWWWZ.......
.......QQRRRRRRSSTTTUW..........XWWVVY..............YXWWVVVVWVVVY.......
......YPPQRRRRRSSSSTTUWY......YVVVVXZ.............YWWWVVUUUVVVVWZ......
......WPPPPQQQRRRSRSTUWY.ZVRRWWVVWXY.............YWWWVVVUUUUUUUWY......
......WOOOPPPQQQQRQRSSPMHJKNQSWWVWXY...........ZXWVWVVVUUUUUUUUWY......
......TONNOOOPPPPOUPOLGEFHJLQSWXVWXYY..VTUY..ZYWWVVVVUUUUTTUUUVY......
......RNNNNOONNMKJLIEDEFGHKMPRVWVWXYX.YTQQOMLNRUXVUUVUUUTTUUUVX......
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......LKKJIJJKGCBABCEFHKKKLOSZ.ZYYZ...WTQONMMMLJIHGGGFHPTSRRSTTUY.....
......KJJJIIIIFCBBCDFHJLKLORV.ZYY......WSPNMMNLKIHHGGFGJSTSRSSSTY.....
......JIIIHHIGDCCDDEGILLLNQTZ.YYY.......UQONMMNLJIHGGGGIPSSQRRRTY.....
......IHHGGGHFDDEEEGIKLLOPSX.ZYYY.......WTPOMMNNKIIHGGHJOTPPQQRSX.....
......IGHGGGGEEEEFFHJKLNPRU..ZZZZ.......ZUSPONNNMJIHHIKKNSOPPPPSV.....
......GFFFFGFEEEFFGIJLLOQSV..ZZZ.........WSRPONNNLJIIJKLMQOONNOQU.....
......FFEEEEFDDDFGIIKLNOPSY..ZZY.........WUSRONMMMKJJJKKLPNONMPSV.....
.....VEFDDEEDEDDFHIIJLNNOQY.ZZZY.........XTTROUNMMLKKKKMNOMMLNSVZ.....
.....TEDDCCCEEEDFGHJKNMMOQX.ZYZY.........XUUPOONMMMKKMNLLMLLPSUW......
......KIDCBBBAABDDIIJKMLNQY.YYYYZ........XUSPOONMMMLLLLLKJMLRUWZ......
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.......WONLKJIFEEEDDGIHDGHIVYYXWY........YUSONMLLLLKLLLJKORTVY........
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..................ZYXWWVUTWYYWUUUVX..YNMMLMNPQRSSTUUVWYZ..............
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Figure 8.- Profilometer output data for cleft palate cast.

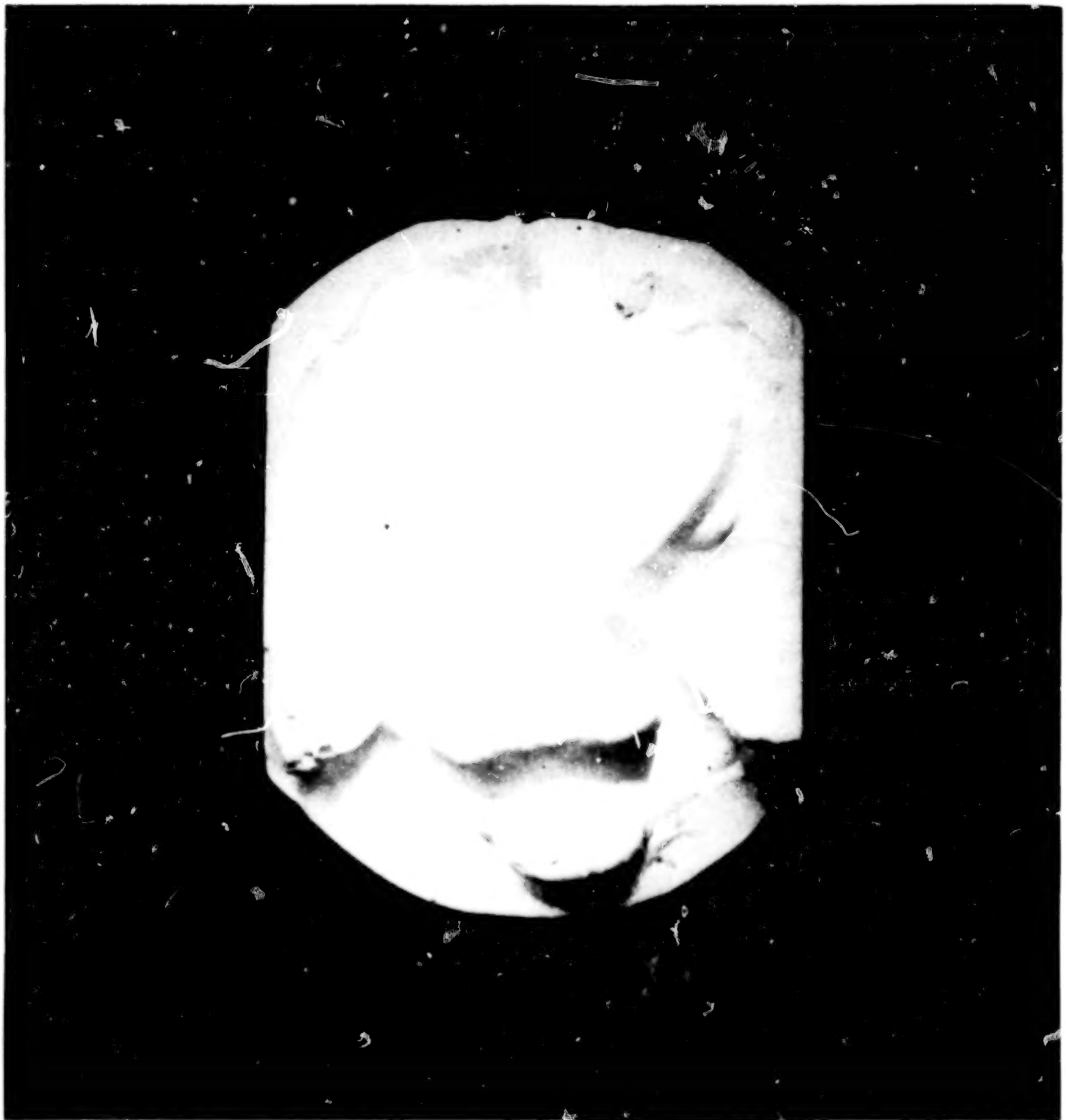

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Figure 9.- Photograph of cleft palate cast.

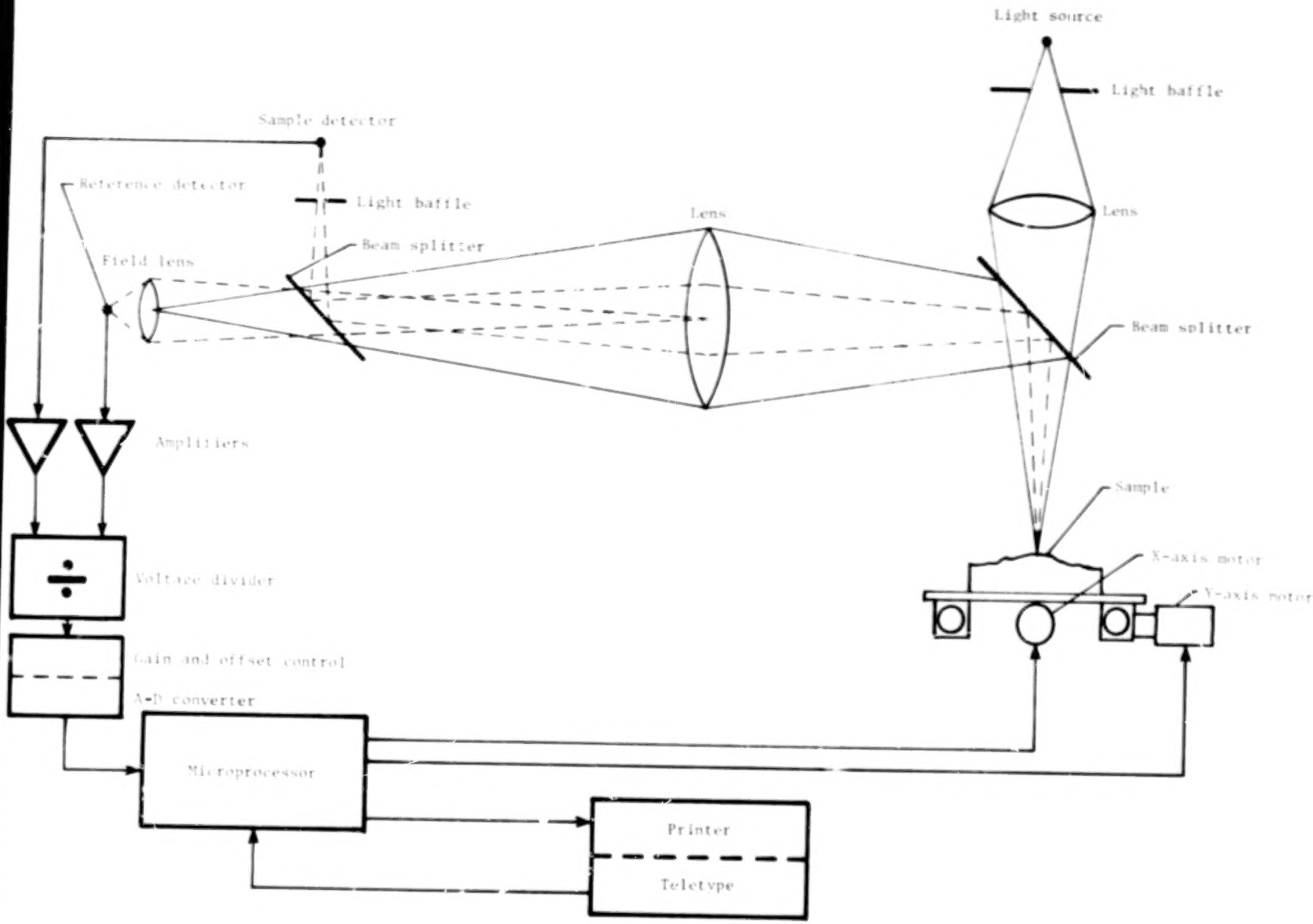

Figure 10.- Improved optical design for optical profilometer.

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16. Abstract

A technique is described for obtaining spatial characterization of three-dimensional surfaces with uniform near-Lambertian reflectance using a noncontact optical profilometer. The design concept and system operation are discussed, and a preliminary evaluation of a breadboard system is presented to demonstrate the feasibility of the optical profilometer technique. Measurement results are presented for several test surfaces; and to illustrate a typical application, results are shown for a cleft palate cast used by dental surgeons. Finally, recommendations are made for future development of the optical profilometer technique for specific engineering or scientific applications.

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